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Vegetation and climate change in the Pro-Namib and Namib Desert based on repeat photography: Insights into climate trends

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ABSTRACT

This paper presents empirical evidence of historical vegetation and climate change in the arid Pro-Namib and hyper-arid Namib Desert spanning the late 19th century to the present based on one hundred archival landscape photographs that have been re-photographed or 'matched'. Each photo site was evaluated for changes in woody cover and taken together serve as a proxy for how climate has changed in the region. Vegetation change was related to values for precipitation and temperature derived from the Global Land Data Assimilation System for the period 1948–2017 as well as the number of fog days expected at a site. The resulting analysis reveals a trend of increased vegetation cover associated with increased precipitation (fog and rain) in the coastal Fogbelt and the inland Savanna transition with a shrinking of the hyper-arid Minimum zone between the two. These findings accord with projected effects of global warming on the Benguela upwelling system but are at variance with regional climate model forecasts that project widespread aridification. In the absence of long-term climate data, the results of this research are an important contribution of evidence-based knowledge of past climate trends and their relationship to future climate change scenarios for the region.

1. Introduction

This research comprises an extensive empirical analysis of historical vegetation change in the hyper-arid Central Namib Desert and the arid Pro-Namib regions of Namibia. Findings are based on the examination of one-hundred repeat photo sites located adjacent to the Atlantic coast of Namibia between the Dune Sea of the southern Namib Desert and the Huab River in the north extending up to 180 km inland. Apart from a few studies of individual repeat photo sites (e.g. Jürgens, 2006) and those that have investigated the effects of climate on vegetation (Hachfeld, 2000; Hachfeld and Jürgens, 2000; Soderberg, 2010) none has shown the relationship between climate and long-term vegetation change and related these findings to future climate change scenarios for the region.

The Central Namib Desert and the adjacent Pro-Namib comprise a gently sloping gravel plain intersected by inselbergs and mountains intercut by several ephemeral rivers that flow infrequently as a result of heavy rainfall in upstream catchments. The biota of the Namib is sustained by two main precipitation types: fog and rain (Hachfeld and Jürgens, 2000). At the coast, cool humid conditions prevail due to the cold sea surface temperatures produced by the Benguela Upwelling System (BUS) where fog is the dominant precipitation source. As the terrain rises to the east, the occurrence of fog declines and ceases to be an important source of precipitation after about 70 km from the Atlantic coast. This declining fog gradient is intersected by a converse rainfall gradient that increases to the east where summer rainfall becomes the most important source of precipitation (Henschel and Lancaster, 2013). Between these two opposing climatic gradients, an area of extreme aridity exists. These distinct contrasting climatic conditions, along with soil types and geomorphology, determine the main vegetation zones that are the subject of this research.

One of the main obstacles to researching climate change in the Namib is the paucity of historical climate data. While long-term weather stations exist at the coast and at the eastern edge of the Pro-Namib, the Central Namib area has been monitored relatively infrequently in the past (Lancaster et al., 1984). For example, west to east

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transects were monitored for rainfall, temperature and fog but these were maintained between 1996 and 2000 only (Hachfeld, 2000; Hachfeld and Jürgens, 2000). Only during the last four to eight years has a permanent grid of ten climate stations been installed (SASSCAL) in the Central Namib. Because of the scarcity of historical climate information, satellite data and interpolated models provide the primary basis of climate change research.

Global and regional climate models predict that Namibia's climate will become increasingly hotter and drier over the course of the 21st century with devastating consequences for the environment. Temperature is expected to rise and rainfall to decline resulting in an expansion of more arid-adapted species into more mesic areas, including those currently dominated by Savanna and Nama-karoo biome elements (Thuiller et al., 2006; IPCC, 2007; Turpie et al., 2010; Engelbrecht and Engelbrecht, 2016). Grasses are expected to decline, as a result of increased aridification but also from an increase in woody plant cover in response to the rise in atmospheric CO_2 (Midgley et al., 2005). The BUS is also expected to undergo significant changes in the next hundred years with important implications for inland environments. Most projections suggest that the incidence of fog will increase (Haensler et al., 2011a) but that this is contingent on changes in the sea/land temperature gradient which in turn will influence wind speed and the upwelling system itself (Bakun et al., 2015).

Because perennial vegetation in this relatively undisturbed environment (Wassenaar et al., 2013) is strongly influenced by climate (Hachfeld and Jürgens, 2000), we regard long-term vegetation change as a proxy for changes in climate. An understanding of how the cover and abundance of perennial plants has changed close to the coast also provides insights into the long-term changes that might have occurred in the BUS and its influence on the occurrence of inland fog and rainfall. Our analysis of a large sample of repeat photographs provides a comprehensive overview of vegetation change in the Central Namib and adjacent areas from the late 19th century to the present. We suggest that by evaluating historical changes in woody vegetation, we can also reveal important insights into the ongoing trends in climate and broaden the interpretation of global and regional climate model projections.

2. Methods

2.1. The spatial and temporal distribution of the repeat photo sites

The one hundred repeat photo sites that were used in this study were chosen on the basis of having been subjected to minimal anthropogenic disturbance between the dates of the original and repeat image thereby isolating the interaction between vegetation and climate without confounding the effects of land-use disturbances. We acknowledge that pre-colonial and colonial impacts on vegetation are evident in several sites used in this study. However, the effects of livestock grazing and colonial transport routes in this arid environment are relatively minor in relation to abiotic factors such as rainfall, fog and temperature (Sullivan and Rohde, 2002).

The area covered extends 180 km inland from the coast and over three degrees of latitude between the ephemeral Aba Huab and Kuiseb Rivers covering an area of approximately 40,000 square kilometers (Fig. 1). The average time-lapse between the date of the original image (spanning 1876 to 1995) and the repeat photograph is seventy-eight years. The historical images were found in a variety of archives and include many from the late German colonial period (1900–1915), just after the 1st WW (1919) and during the South African rule in the 1950s and 1960s. Many of these photographs were found in collections made by botanists and geographers that were taken with the explicit purpose of recording vegetation and landscapes. Several sites are also associated with iconic landmarks in the region or with major transport routes or large ephemeral rivers along which early photographers traversed the landscape when moving from the coast to the hinterland. The sites are located in a range of different tenure regimes including state land, privately-owned land and communally-managed properties.

2.2. Field surveys and the delimitation of vegetation zones

The site survey methodology is described in detail by Rohde and Hoffman (2010).

At each site we first identified discrete landform units (e.g. sandy plains, rocky hills, ephemeral rivers) present in the landscape. We then surveyed the site by walking through the main vista represented in the photograph and listing the percentage cover of the dominant species in each landform unit. Notes on major changes in species composition and the cover of species in different landform units were recorded on site. In this study we follow the nomenclature of Klaassen and Kwembeya (2013).

Based on an assessment of the dominant species we assigned the landform units at each site to one of the vegetation units identified by Jürgens et al. (2013) in their more detailed phytosociological analysis of the region (Supplementary Material, Table 1). These units were further consolidated into four broad vegetation zones: Fogbelt, Grass/shrublands, Savanna transition and Large ephemeral rivers. At 13 sites, two or more vegetation units were identified, thereby increasing our dataset to 115 separate units of analysis. However, to avoid pseudoreplication (Hurlbert, 1984), all vegetation units within one kilometre of each other were grouped. This resulted in a reduction of the dataset to seventy-five sites (Table 1).

2.3. Estimating the change in the percentage cover of woody vegetation

Several methods can be used to quantify and interpret changes visible in the landscape depending on the research questions, the level of detail required and the type of habitat under investigation (Munro et al., 2008; Nyssen et al., 2009; Webb et al., 2010).

The percentage cover of each species (and total cover of woody vegetation) was estimated during the field surveys as outlined in 2.2. These estimates were used as a baseline to evaluate the total change in cover between the archival image and the repeat. This was accomplished by ocular comparison of the exactly matched digitised photographs (Carlsson et al., 2011). In some instances the values for woody vegetation cover derived from the field surveys were verified using an aerial assessment of woody cover in Google Earth Pro. If necessary, the percentage values at a site were adjusted accordingly.

At twelve sites, field survey data were not available. For these sites, ocular estimates of the percentage woody cover were carried out using digitised calibrated reference images (Roush et al., 2007; Galegos and Glimskär, 2009). These reference images were derived from sites where the percentage cover was verified by site surveys and satellite imagery. Reference images were then compared to repeat photos where survey data were not available. This enabled us to obtain cover estimates and to compensate for the distortion due to the oblique view of the landscape image. Again, these results were calibrated with estimates of woody cover using satellite images of each site. We believe that this combined methodology represents an innovative advance on previous vegetation studies which have used repeat photography to analyse ecological processes (Webb et al., 2010).

2.4. Climate data acquisition and verification

Climate data acquisition and analysis was performed in the Google Earth Engine cloud computing platform for geospatial analysis. Daily values for total precipitation rate [kg/m^2/s] (including fog and fog drizzle) and air temperature [K] were extracted for each site from the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004). Data were aggregated to daily mean values and used as explanatory variables for woody vegetation change.

The validity of the data for precipitation and temperature derived

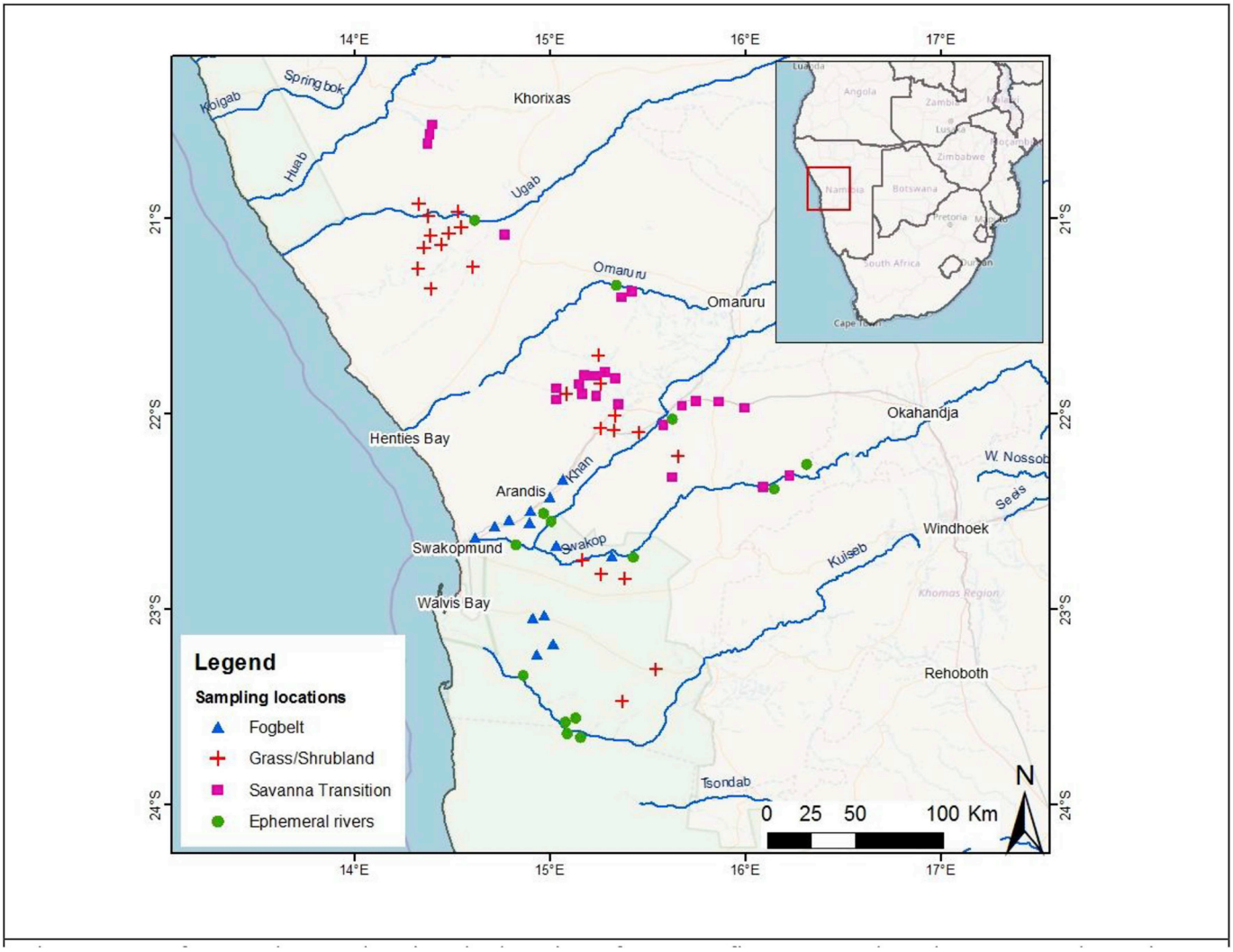

Fig. 1. Map of research area showing the location of seventy-five (grouped to 1 km) repeat photo sites (Table 1). Symbols have been slightly 'dispersed' in order to clarify the positions of sites, particularly where two or more vegetation units were present.

Table 1
The total number of historical photographic sites in each of four vegetation zones in the Central Namib and those > 1 km apart which were used in the final analysis.

Vegetation Zone	No. of sites	Sites > 1 km apart
Fogbelt	18	13
Grass/shrublands	31	24
Savanna transition	38	24
Large ephemeral rivers	28	14
Total	115	75

from GLDAS was tested using ground-based historical climatic data from the following Southern African Science Service Centre for Climate Change and Adaptive land Management (SASSCAL http://www.sasscal.org) weather stations: Wlotzkasbaken (2011-04-05 – present), Ganab (2014-09-01 – present), Numees (2015-10-21 – present), Vandersterrberg (2015-09-30 – present) and Yellowdune (2015-09-30 – present). The precipitation and temperature values derived from GLDAS were significantly correlated ($p < 0.0001$) with the SASSCAL station records.

2.5. Fog occurrence

Reliable fog occurrence and fog precipitation data are limited to very recent weather station measurements (SASSCAL). These include a weekly record of fog precipitation across a transect between the coast and 70 km inland during 1997–2000 (Hachfeld, 2000). It also includes the Gobabeb Research Station's network of nine meteorological stations situated in the southern Central Namib spanning (with many breaks in the time series) the late 1960s to the early 1980s (Lancaster et al., 1984). Consequently, we rely on a fog occurrence map of the Namib (Mendelsohn et al., 2002) derived from an analysis of satellite imagery in 1984 (Olivier, 1995). The position of our sites was interposed on this map in order to estimate fog days per year for each site. Where a site was closest to an isoline, that value was attributed to that site; where the site was closer to the mid-point between isolines, the mean value was attributed.

2.6. Statistical analyses

Even though we re-photographed 100 sites and assessed woody vegetation cover in 115 vegetation units, after grouping sites which were less than 1 km apart, sample sizes of each vegetation zone were relatively small (13–24 sites; Table 1). This precluded a thorough assessment of the assumptions underlying most parametric statistical

methods and limited our ability to fit complex models that may well be necessary to detect more subtle relationships between climate and vegetation change. We therefore used simple statistical tests based mostly on non-parametric methods.

Differences between vegetation units in terms of their mean distance from the coast, elevation and climate variables were tested using a Kruskal-Wallis test and differences compared using Dunn's multiple comparison procedure. Annual change in vegetation and climate variables was calculated using the period between the historical and repeat dates. An assessment of whether significant changes (e.g. in woody cover, or climate) occurred was performed using one-sample Wilcoxon signed-rank tests. The association between vegetation change and average climate or climate change variables was assessed using Spearman rank correlations. Owing to the small sample sizes, failure to reject the null hypothesis should therefore only be interpreted as a failure to observe a large difference between samples. Analyses were conducted in R version 3.4.0 and Microsoft Excel.

3. Results

3.1. Photographic evidence of woody cover change in each of the vegetation zones

Table S2 provides a broad overview of the historical and repeat photo details and the changes in woody plant cover recorded in each of the four main vegetation zones in the Central Namib over the period 1876 to 2016. We include several repeat photo pairs to illustrate the main changes recorded in the four vegetation zones of the Central Namib with additional information (Table S2) and matched pair examples (Figs. S3–6) included in the Supplementary material.

3.1.1. Fogbelt

In the repeat photographs of the Fogbelt zone the average percentage cover of woody plants was below 4% although a value as high as 10% was also recorded (Table S2). The dominant woody species were *Arthraerua leubnitziae*, *Zygophyllum stapfii* and *Acacia reficiens* amongst a few others (Fig. 2 and Supplementary Material Fig. S3). Woody cover in the more western portion of the Fogbelt zone (9 km–35 km from coast) increased by 0.36% per year over 97 years while sites between 40 km and 74 km from the coast showed very little change (0.003% per year) during the average 89 years between the original and repeat images. Over the study period woody cover declined in only two of the 13 Fogbelt sites, both of which were located 50 km from the coastline towards the eastern margin of this vegetation zone.

3.1.2. Grass/shrublands

The average % cover of woody vegetation in the Grass/shrubland zone was more than twice the average value for the Fogbelt zone (Table S2). However, unlike in the Fogbelt zone, woody cover in the majority of sites in the Grass/shrublands did not increase over the sampling period (Fig. 3 and Supplementary Material Fig. S4). In four of the 24 sites woody vegetation cover did not change at all while in 12 of the sites, woody cover declined overall by between 0.5 and 3.3%. The average change in woody cover was only 0.007% per year for the 73 years between the original and repeat images and variability in woody cover change was also relatively low in this vegetation zone. In seven of the eight sites located in the more eastern part of the Grass/shrublands (i.e. 92 km–125 km from the coast) woody plants, more typical of the Savanna transition vegetation zone such as *Acacia mellifera, A erubescens, A. reficiens, Maerua* spp. and *Grewia* spp., have increased in cover.

Fig. 2. Fogbelt (near Rossing Mt.) Matched photographs (33 km from coast) showing examples of the long-lived *Arthraerua leubnitziae* plants between 1919 (top) and 2016 (below) displaying the same individuals in each image (white dots). The population of this species has doubled during the last 97 years (green (gray) dots) due to increased fog. Mortality of individuals is shown as red (dark) dots. Other species include *Zygophyllum stapfii* and *Acacia reficiens*. Photo credits: Pole-Evans (SANBI); Rohde and Hoffman. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. Grass/shrublands (Aukas East). Matched photographs of *Euphorbia damarana*, *Calicorema capitata* shrubland (110 km from coast) illustrating slight decrease in cover (from 14% to 13%) over 97 years between 1919 (top) and 2016 (below). The replacement of *E. damarana* by savanna species (white dots) such as *A. reficiens, A. mellifera, Adenolobus pechuelii,* and *Maerua parvifolia* and *Commiphora* spp. is indicative of the westward expansion of savanna rainfall. Photo credits: Pole-Evans (SANBI); Rohde and Hoffman.

3.1.3. Savanna transition

The Savanna transition zone is comprised of a large number of woody species but is dominated by *A. reficiens, A. mellifera, A. erubescens, Boscia foetida* and *C. mopane* (Fig. 4 and Supplementary Material Fig. S5). In the repeat photographs, average values for woody plant cover were nearly twice those of the Grass/shrubland zone (Table S2). Woody plant cover declined in one site only and remained the same in four of the 24 sites in the Savanna transition zone. The average rate of increase in woody plant cover was 0.07% per year. Species composition in Savanna transition sites varied in relation to latitudinal position where the hotter northern sites were dominated by *C. mopane* in contrast to southern sites where acacia species predominated.

3.1.4. Large ephemeral rivers

The sites located within azonal Large ephemeral rivers of the Kuiseb, Swakop, Khan, Omaruru and Ugab Rivers are dispersed throughout the Fog, Grass/shrubland and Savanna zones. Woody plant cover was greatest in this vegetation zone with values as high as 75% recorded at one location. A wide range of woody plants dominated the ephemeral rivers including *Faidherbia albida*, *Acacia erioloba, Tamarix usneoides* and *Salvadora persica* amongst others. Although changes in woody plant cover varied considerably between sites in this zone, it nearly doubled over the study period with average values of 0.26% per year (Fig. 5, Supplementary Material Fig. S6). Only two sites exhibited a decline in woody plant cover with relatively modest reductions in cover of 1% and 5% respectively. The Large ephemeral rivers were also characterized by a noticeable increase in alien species over time, especially *Prosopis* spp. Each river presents distinct traits in relation to vegetation change: e.g. the Khan is the most stable in terms of species and percentage cover; the Kuiseb appears to be the most dynamic and the Swakop the most impacted by anthropogenic disturbance and alien species.

3.2. The distribution of sites in relation to the underlying environmental gradient

The region is characterized by a distinct environmental gradient from the coast inland (Fig. 6, Table 2). Elevation increases linearly with distance from the coast although sites within the Large ephemeral rivers are generally located at lower elevations than other sites at comparable distances from the coast. Mean annual precipitation (fog and rain) is relatively low for sites in the Fogbelt and Grass/shrubland sites but increases in Savanna transition sites and sites within Large ephemeral rivers farthest from the coast. Mean annual temperature is lowest in the first 60 km within the Fogbelt zone and is higher further inland although considerable variability exists between sites. The number of fog days declines steeply away from the coast and provides relatively little moisture input for sites further than 100 km from the ocean, and especially for those in the Savanna transition zone.

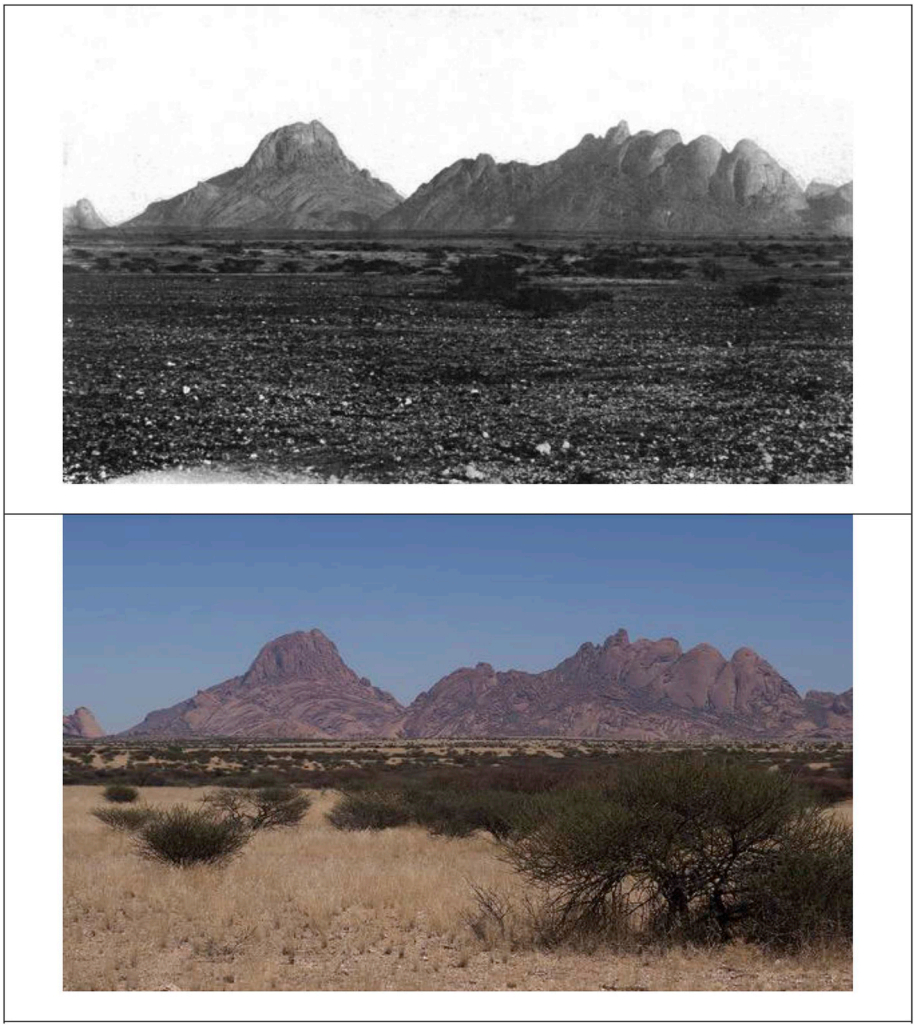

Fig. 4. Savanna transition (Black Range southeast of Spitzkoppe). Matched photographs in eastern desert plains (92 km from coast) show a large increase in woody cover (from 3% to 8%) over 84 years between 1931 (top) and 2015 (below). Dominant species: *Acacia reficiens, Boscia foetida*. Photo credits: The Blue Book, 1931 (National Archives of Namibia), Rohde.

3.3. The cover of perennial woody vegetation along the gradient now

Large ephemeral rivers receive significant inputs of moisture from their upstream catchments and are generally uncoupled from prevailing climate. In addition, ground water is often easily accessible to deep-rooted, woody plants. Because of this, sites which occur in Large ephemeral rivers have been excluded from the analysis in Fig. 7 which shows how the cover of woody plants, as recorded in the repeat photographs, varies along the environmental/climate gradient. The data show that the cover of woody plants increases significantly ($p < 0.05$) with distance from the coast, and with elevation and precipitation, and decreases significantly ($p < 0.05$) with the number of fog days. The relationship between woody plant cover and temperature was not significant ($p > 0.05$).

3.4. Change in the percent cover of perennial woody vegetation

There has been a significant increase ($p < 0.001$) in woody plant cover in the repeat photographs relative to the values in the original photographs in the Large ephemeral rivers (mean annual % change (mapc) = 0.25, se = 0.07, $p < 0.001$, Figs. 8 and 9, Table S2) and Savanna transition zone (mapc = 0.07, se = 0.02, $p = 0.005$). The increase was nearly significant (mapc = 0.01, se = 0.005, $p = 0.054$) in the Fogbelt. No evidence of significant change in woody plant cover over time was found in the Grass/shrubland zone (mapc = 0.007, se = 0.009, $p > 0.1$). Even though the absolute % change in woody plant cover in the Fogbelt was just over 1% (Table S2), in relative terms this represents an average increase of nearly 40% in woody plant cover over the study period (Fig. 9). For the Grass/shrublands, Savanna transition and Large ephemeral rivers the equivalent values for the relative change in woody plant cover were 2%, 48% and 99% respectively.

3.5. Change in the percent cover of perennial woody vegetation in relation to precipitation, temperature and fog day occurrence

The relationship between the percentage change in woody cover and climate is assessed without inclusion of the data for Large ephemeral rivers. The results indicate that there is a significant positive relationship ($p < 0.001$) between mean annual precipitation and the % change in woody plant cover. The relationship is not significant ($p > 0.05$) between mean annual temperature and percentage change in woody plant cover and is significantly negative ($p < 0.01$) between the number of fog days and the % change in woody cover (See Fig. S7).

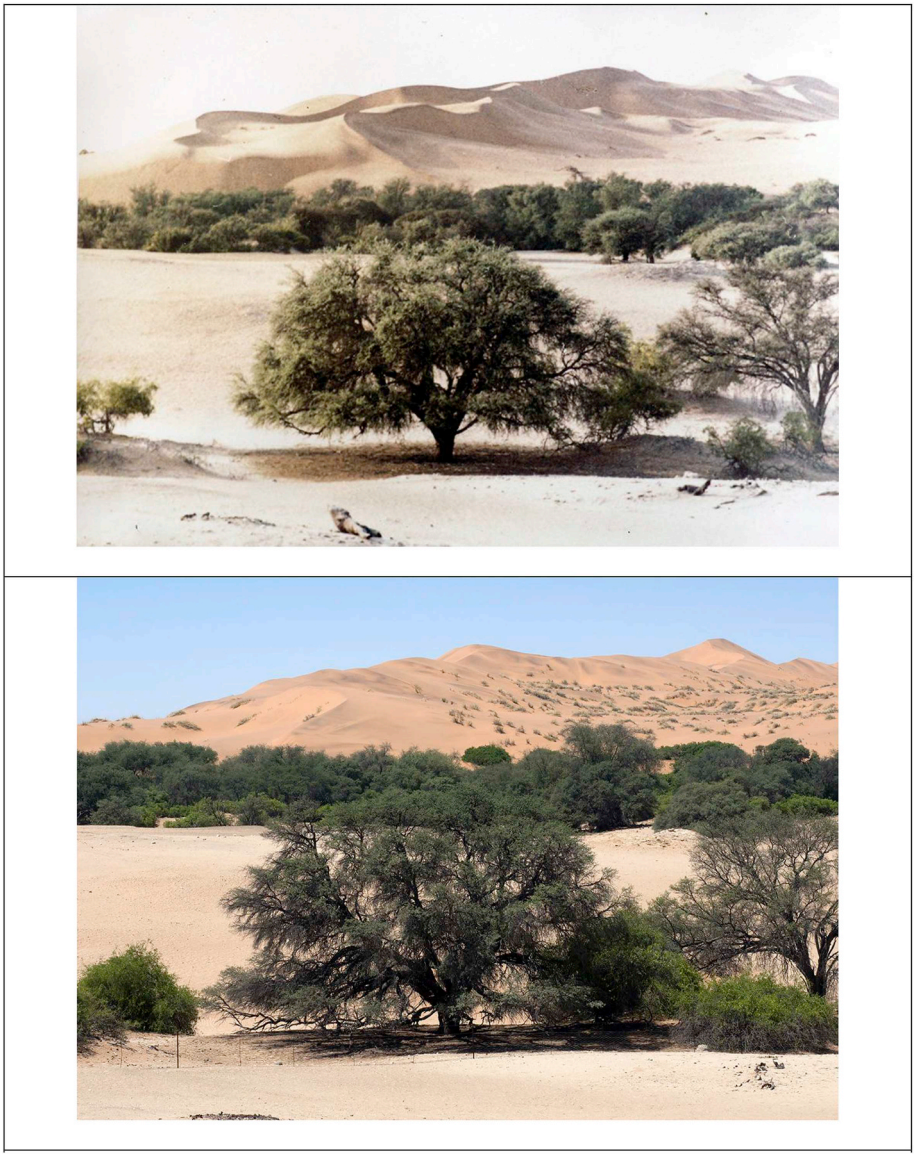

Fig. 5. Large ephemeral river (Kuiseb). Matched photograph from Gobabeb (55 km from coast) illustrating significant thickening and size increase of riverine woody cover over 50 years between 1965 (top) and 2015 (below). Dominant riverine species: *F. albida, T. usneoides, A. erioloba, S. persica.* Photo credits: Unknown (Gobabeb Archives), Rohde.

3.6. Change in precipitation and temperature values over time and their relationship to the % change in woody cover

Between 1948 and 2017 results from GLDAS suggest that mean precipitation (including fog) has increased significantly across all the vegetation zones mean annual change = 0.504 mm (1.6×10^{-8} kg/m^2/s, se = 6.0×10^{-9}, $p < 0.01$) and appears greatest in the Savanna transition zone (Fig. 10). Mean annual temperature has also increased across all vegetation zones (mean annual change = 0.05°C, se = 0.005, $p < 0.001$) but has increased least in the Fogbelt zone. The greatest increase in temperature has occurred in the Grass/shrubland zone although there is considerable variability between sites. The relationship between changes in woody cover and changes in precipitation and temperature across all vegetation zones and within each individual vegetation zone is non-significant ($p > 0.05$).

4. Discussion

4.1. Trends in woody cover change in relation to climate

Woody cover has increased significantly across all vegetation zones apart from the Grass/shrublands. Rainfall and temperature have also increased significantly across all zones. While mean annual precipitation is positively correlated with woody plant cover, the change in precipitation is not related to woody plant cover change. The climate change data show that there have been shifts in precipitation big enough to take a site from 'dry' to 'wet', but the relationship between *change* in precipitation and change in woody cover remains obscure. The most parsimonious explanation for this inconsistency is that there is too much natural variability within a small sample to detect this relationship. That temperature is not associated with woody cover change is especially pertinent in relation to modelled predictions of aridification in the region.

The IPCC (2007) predict higher temperatures (between 2 and 6 °C by 2050), lower rainfall (20% decline by 2080 in the central regions), lower humidity and higher rates of evaporation resulting in soil

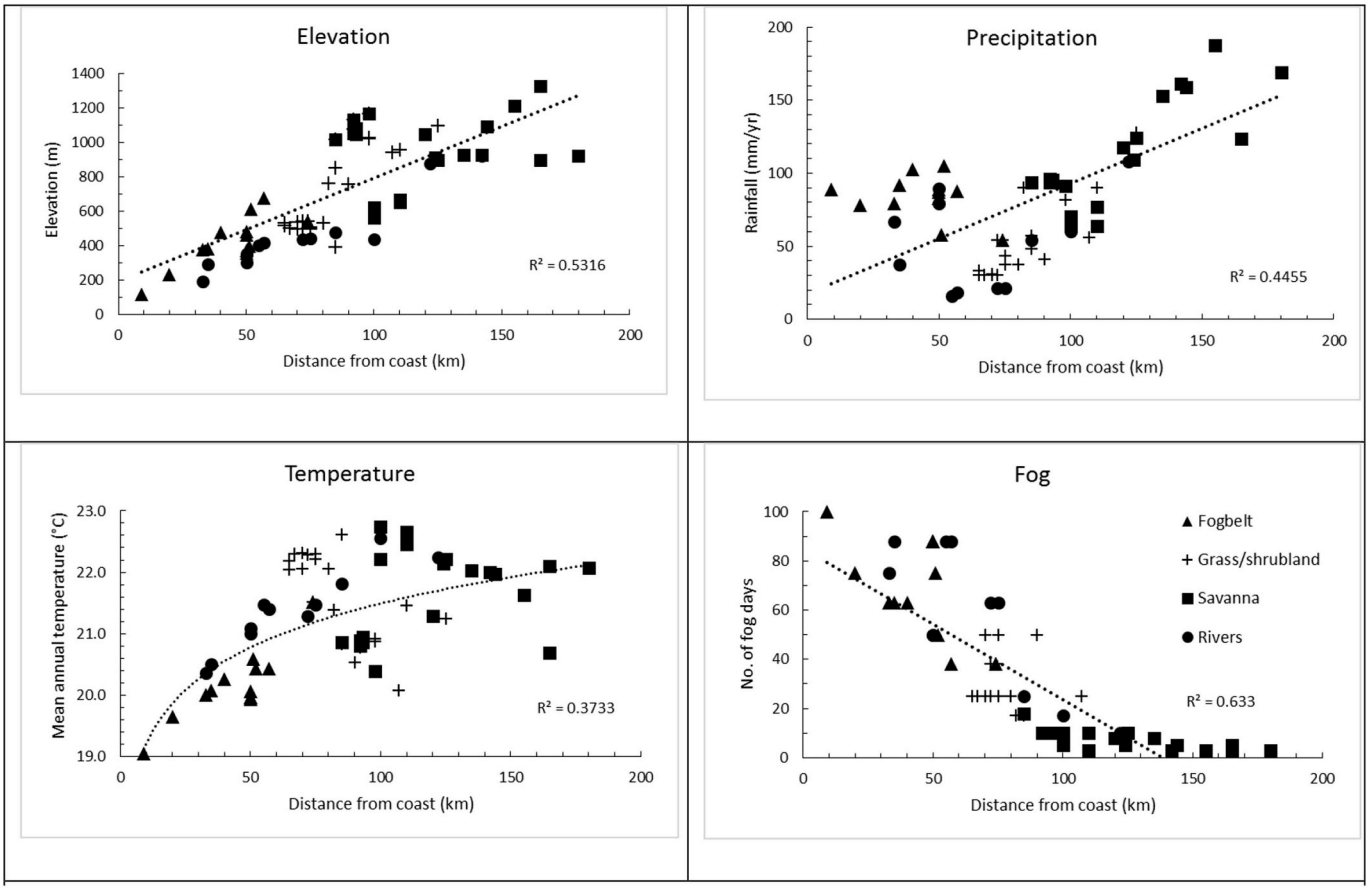

Fig. 6. The change in elevation (m), mean annual precipitation (mm/yr), mean annual temperature (°C) and the number of fog days per year with distance from the coast and within the four main vegetation zones which occur in the Central Namib.

moisture levels declining dramatically with severe implications for plant growth. Modelled simulations of the effects of anthropogenic climate change on the vegetation in the arid parts of Namibia and Southern Africa predict an expansion of arid vegetation (Hulme et al., 2001) general aridification and reduced ground cover (Thuiller et al., 2006). The Namib is predicted to experience heat stress and higher rates of evaporation, lower rates of aquifer recharge and subsequent decline in plant cover in the Large ephemeral rivers (IPCC, 2007). Reductions in plant cover and productivity are also predicted in Southern African savannas in response to drying trends (Woodward and Lomas, 2004) and Savanna and Nama-karoo biomes are forecast to advance at the expense of the grasslands (Dixon et al., 2003). Midgley et al. (2005) suggest that Namibia's dominant vegetation type, grassy savanna, will lose its dominance to desert and arid shrubland vegetation types and that rising atmospheric CO_2 will promote bush thickening (Bond and Midgley, 2000; Bond et al., 2003). Finally, Engelbrecht and Engelbrecht (2016) predict between 42% and 80% expansion of the hot desert zone in southern Africa under IPCC AR4 scenarios.

The time series analysis of the GLDAS data for the period 1948–2017 supports the projected increase in temperature advocated by most climate change models. For precipitation, however, instead of a decline over time there has been an increase. Our analysis does not support the hypothesis of aridification or that plant cover will decline. Because of the aridity gradient however, woody plant cover has not increased the same in all vegetation zones. It has increased most in the Savanna transition and in the Large ephemeral rivers. While we acknowledge the potential role of CO_2 fertilisation on bush thickening, several caveats exist (Hoffman et al., 2011) including other factors that could be responsible, such as changes in rainfall, temperature and land use practices (Rohde and Hoffman, 2012).

Part of the difficulty in analysing trends in cover and climate in the Namib and Pro-Namib is the existence of two distinct and opposite climate gradients: the fog gradient declining in an inland easterly direction and the rainfall gradient that declines towards the coast.

Table 2
The main environmental characteristics of the four vegetation zones analysed in the Central Namib region. Values reflect mean ± stdev and (range) for the photographic site locations within each zone. Significant differences were tested using a non-parametric Kruskal Wallis test with a Dunn's multiple pairwise comparison. Dissimilar superscripts denote significant differences at $p < 0.05$ level.

Environmental Variable	Vegetation zone			
	Fogbelt (n = 13)	Grass/shrubland (n = 24)	Savanna transition (n = 24)	Ephemeral rivers (n = 14)
Distance from the coast (km)	44 ± 17^{a} (9–74)	85 ± 16^{b} (65–125)	117 ± 29^{c} (85–180)	87 ± 48^{b} (33–180)
Elevation (m)	421 ± 148^{a} (115–675)	744 ± 262^{b} (390–1166)	978 ± 192^{c} (560–1328)	525 ± 59^{a} (190–923)
Mean annual precipitation (mm)	84 ± 14^{a} (54–105)	61 ± 29^{a} (30–128)	114 ± 41^{b} (64–224)	73 ± 52^{a} (16–169)
Mean annual temperature (°C)	20.1 ± 0.6^{a} (19.0–21.5)	21.5 ± 0.7^{b} (20.1–22.6)	21.5 ± 0.7^{b} (20.4–22.7)	21.5 ± 0.6^{b} (20.4–22.6)
No. fog days	71 ± 20^{c} (38–100)	24 ± 13^{b} (8–50)	8 ± 4^{a} (3–18)	45 ± 34^{b} (3–88)

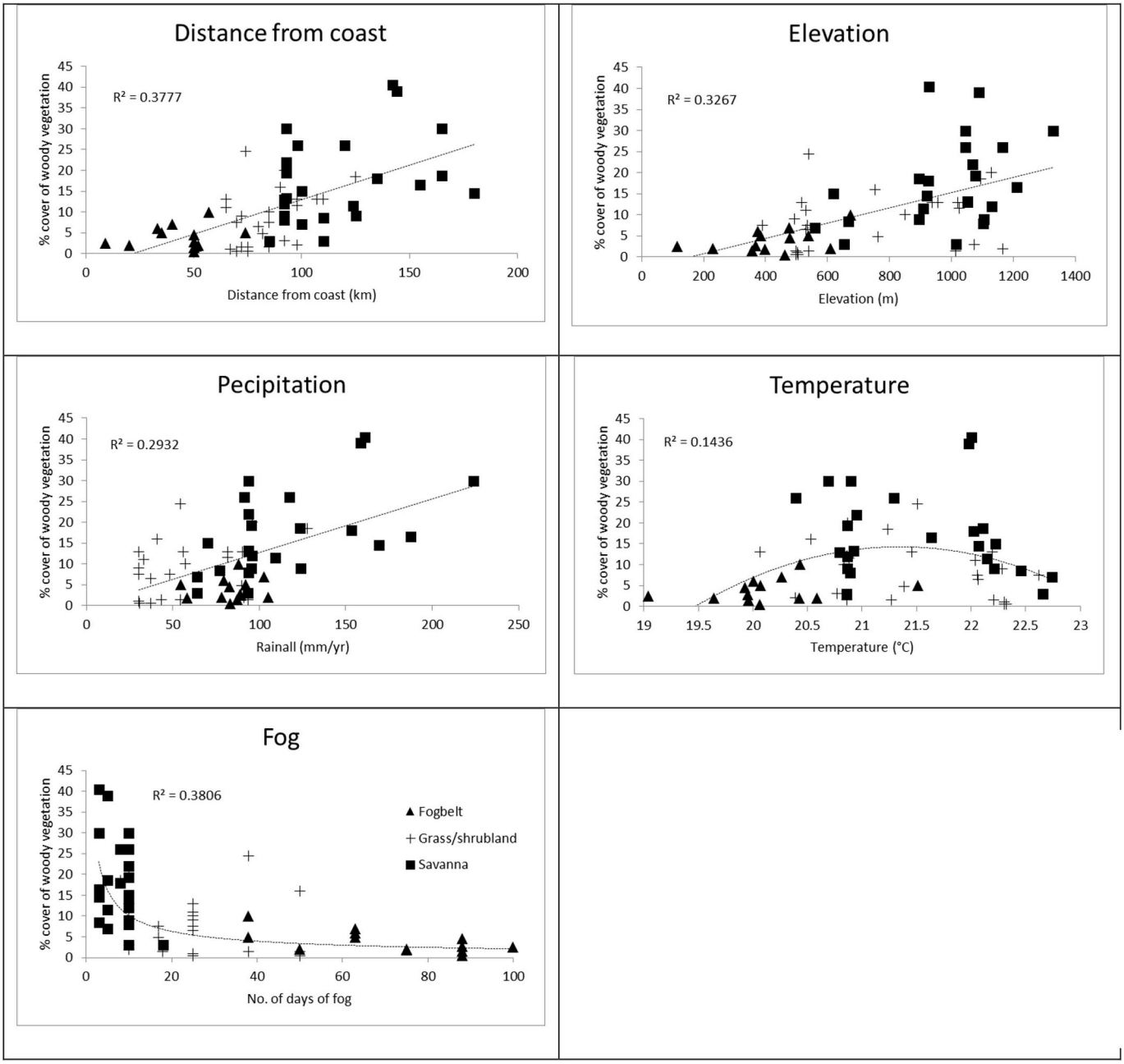

Fig. 7. The % cover of woody vegetation estimated from the repeat photographs in relation to distance from the coast (km), elevation (m), mean annual precipitation (mm/yr), mean annual temperature (°C) and the number of fog days per year within three of the main vegetation zones (i.e. excluding Large ephemeral rivers) in the Central Namib.

Between the two, there exists a hyper-arid zone of minimum vegetation cover which overlaps, to some extent, with the eastern Fogbelt and the western Grass/shrubland zone. When analysing the relationship between climatic variables and woody cover change across these disparate climate zones, we are not always evaluating like for like. For example, vegetation in the Fogbelt zone is not dependent on average rainfall while vegetation in Savanna transition zone is not affected by fog. Furthermore, the influence of temperature in the Fogbelt plays a different role than it does in the Grass/shrublands or the Savanna transition zones.

Several studies have documented the various vegetation communities, growth forms, species diversity, percentage cover and biodiversity response to climatic conditions in the Central Namib between the coast and the inland savanna (Moisel and Moll, 1981; Hachfeld, 2000; Hachfeld and Jürgens, 2000; Soderberg, 2010; Jürgens et al., 2013). While the vegetation units they discuss are similar (or the same) as those outlined in this study, they also describe an area of extreme climatic conditions characterized by very high temperatures, low air humidity and an almost total lack of precipitation from either fog, dew or rain that coincides with and overlaps these vegetation units (Hachfeld, 2000; Hachfeld and Jürgens, 2000). This Minimum Zone can be defined as an area with extremely low woody vegetation cover so that climate and vegetation become interchangeable as indicators of extreme hyper-arid conditions.

We suggest from our analysis that the Minimum Zone has contracted in its western and eastern reaches due to changing climatic conditions during the period covered by our study. Evidence from the original photographs indicates that historically the Minimum Zone spanned the entire Fogbelt, the Grass/shrublands and part of the western Savanna transition from 9 km up to 110 km from the coast. Today,

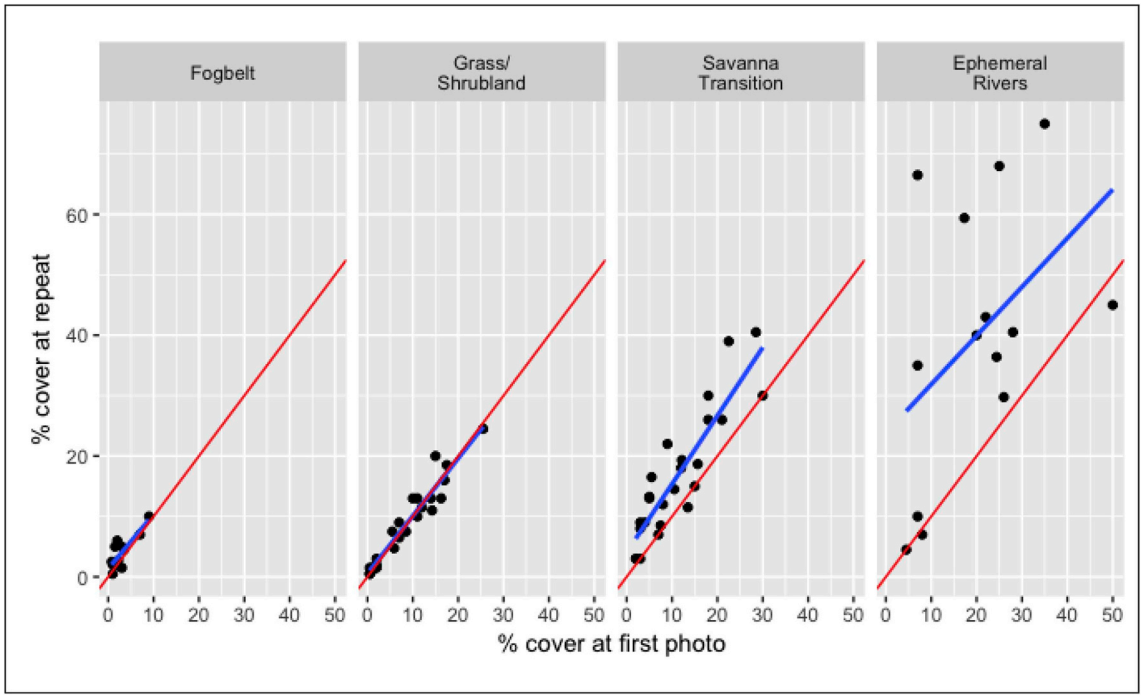

Fig. 8. The relationship between historical woody cover and woody cover in the repeat photos. Each vegetation zone is shown separately. The blue line indicates the line of best fit to the data; the red line is the line y = x, which would indicate no change. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the Minimum Zone is smaller, starting from mid-way in the Fogbelt, about 40 km from the coast and ending in the eastern part of the Grass/shrubland zone about 90 km from the coast.

Within the Minimum Zone we find no relationship between percentage cover change in woody vegetation and changes in temperature, precipitation from fog and rainfall. We attribute the small variations in cover change to site variability (micro habitat, geomorphology, soil types), to the differential responses of a large number of vegetation types included in this category (Table S1) and to the disparities created by particular landscape views as framed in the repeat photographs. An increase in the incidence of fog is probably responsible for the historical changes observed in the eastern Fogbelt zone. However, in the eastern part of the Grass/shrubland zone increased rainfall probably accounts for the westward incursion of savanna species. This expansion of woody plants into what were historically more arid environments also appears not to be a new phenomenon. Historical accounts such as those of Gerald McKiernan in 1874 describe Usakos (125 km from the coast) as "the beginning of the grass country" on the edge of a treeless "desert tract" (McKiernan 1954: 37). Today, Usakos lies well within the Savanna transition. Other photo sites in this eastern region of the research area verify the process of widespread and progressive bush encroachment throughout the 20th century (Rohde, 1997; Rohde and Hoffman, 2012) which appears related to the increase in rainfall suggested by the GLDAS data for the period 1948–2017.

The azonal Large ephemeral river sites are dispersed across the Kuiseb, Swakop, Khan, Omaruru and Ugab Rivers. Changes in

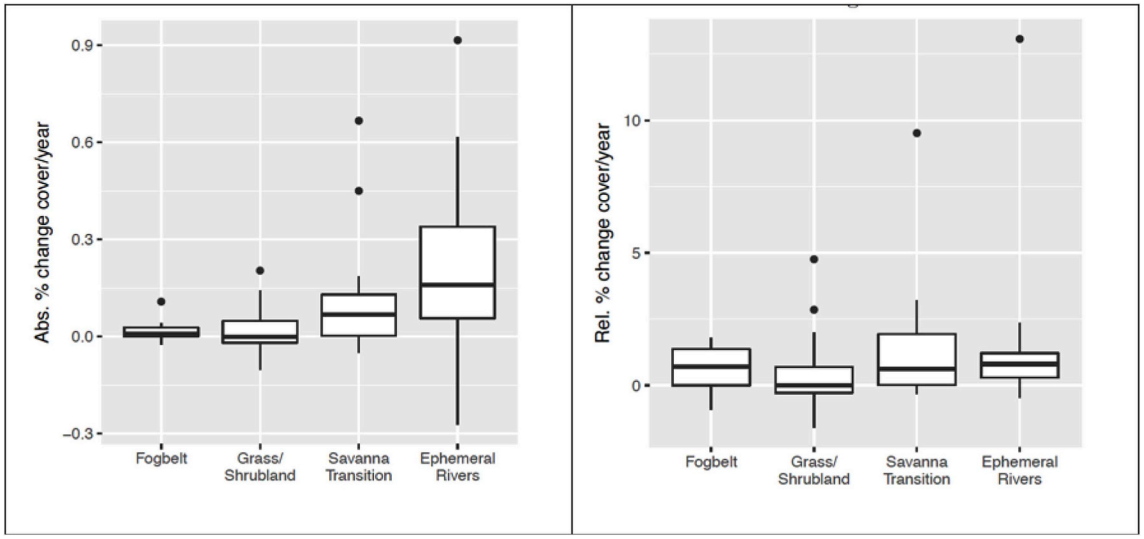

Fig. 9. Boxplots displaying the distribution of absolute (left) and relative (right) changes in woody cover in four vegetation zones. Note the importance of relative increases in cover in the sparsely vegetated Fogbelt.

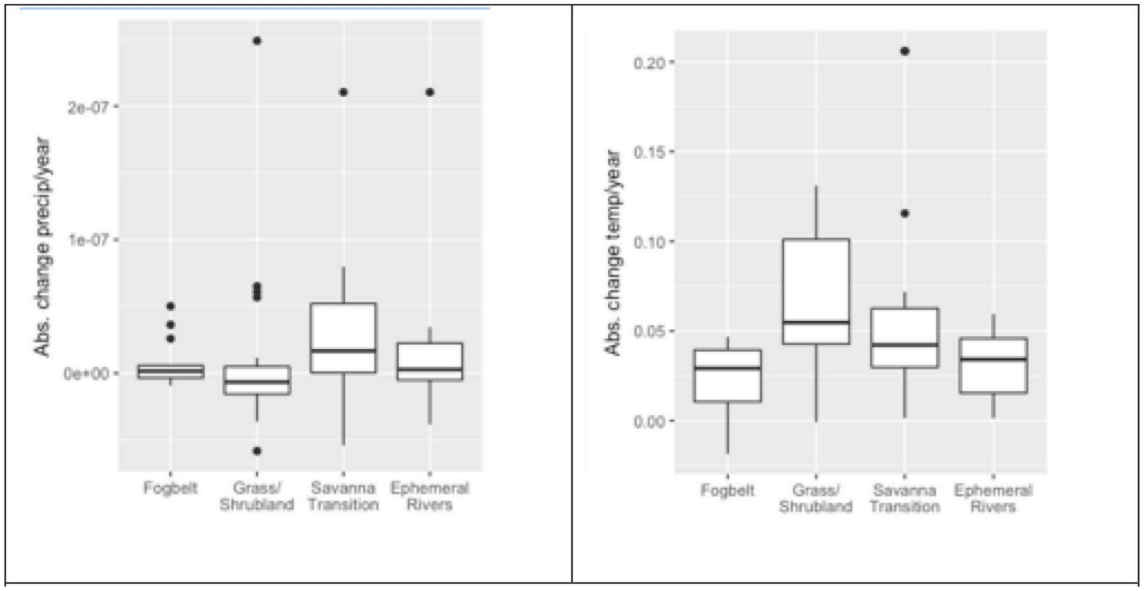

Fig. 10. Boxplots displaying the distribution of absolute changes in precipitation (left) and temperature (right) per year. Total precipitation = kg/mˆ2/s. Temperature in degrees K.

vegetation in these riverine systems are largely contingent on factors unrelated to the climate of any specific site since catchment size and management (e.g. dam-building, water extraction), alluvial aquifer profiles, upstream land-use and the degree of invasive alien species all influence their hydrology and thereby contribute to the vegetation dynamics at each site. However, despite the influence of external factors on the hydrological dynamics of ephemeral river systems, we found a significant relationship between woody cover change and annual precipitation. As reported by Rohde and Hoffman (2012), riverine sites with higher rainfall amounts showed the greatest increase in woody plant cover.

4.2. The influence of oceanic and atmospheric conditions on vegetation change

The Benguela upwelling system (BUS) is one of the most important influences on climate in the Central Namib and adjacent areas. And because it is responsible for one of the most productive fisheries in the world, it has been subject to extensive research involving the effects of global warming on the winds that drive coastal upwelling and the resulting sea surface temperatures that influence fog occurrence and rainfall. Our findings confirm that past climatic trends as revealed by our investigation of vegetation change are in accord with modelled future projections of trends associated with the effects of global warming on the BUS.

Using a regional climate model (REMO) Haensler et al. (2011a, 2011b) predict a slight increase in the number of fog days at the coast and a slight decrease for more inland areas and even the disappearance of fog in many locations by 2081–2100. They claim that this dipolar pattern of change is related to increases in temperature. However, this projection is based on only one, twenty-year time slice for a control. Our historical evidence takes in a much longer time-slice and generally accords with the Haensler et al. (2011b) projected trend.

Global warming is forecast to result in intensified and colder upwelling in all four major Eastern boundary upwelling systems. Relative changes in the sea/land temperature gradient are projected to steepen the cross-shore pressure gradients that drive upwelling winds (Bakun, 1990; Bakun et al., 2010, 2015). Stronger upwelling of the cold BUS will result in more coastal fog and heat loss to a colder ocean will result in a less humid airflow inland of the coastal zone. This predicted outcome accords with our findings. There is a growing consensus from General Circulation Model (GCM) projections that coastal winds will intensify in the BUS during the twenty-first century (Lamont et al., 2018; Rykaczewski et al., 2015). Our findings tend to support this later claim.

The occurrence of extreme rainfall events in the Namib and Pro-Namib are associated with Benguela warm SST anomalies known as Benguela Niños (BN). The incursion of warm water across the northern Angola/Benguela Front into the northern BUS is statistically related to rainfall extremes in the Namib and northern/western Namibia generally (Williams et al., 2008). These warm events are associated with the interaction of synoptic moisture fluxes from the southeast Atlantic, southwest Indian Ocean SST anomalies and ENSO but are beyond the scope of this paper to describe in more detail. The relevant issue is the effect of BNs on vegetation change in the research area. Rainfall anomalies associated with BN events have occurred eleven times during the last sixty-five years. In ten of these, increased rainfall anomalies have occurred somewhere in northern Namibia and five of these (1963, 1986, 2001, 2006, 2011) have resulted in widespread and significant positive rainfall anomalies in the study area (Reason and Smart, 2015). The evidence of vegetation change would suggest that increased recruitment events are associated with an increase in positive rainfall anomalies associated with BN in these arid and hyper-arid areas. Jürgens et al. (2013) observed that the highest rainfall on record in 1934 did not result in the recruitment of new *A. leubnitziae* individuals at a site 40 km from the coast. However, closer to the coast there is strong evidence that recruitment events have occurred in the last 100 years. It is plausible to attribute this change to an increase in BN frequency since 1963 because the germination and establishment of Fogbelt species are unlikely to occur from fog precipitation alone.

5. Conclusion

Past climate trends are not predictors of future trends but they do inform our understanding of the causes of present conditions. A tipping point might reverse a historical trend but we see no evidence of this from our analysis of woody vegetation change in the Namib and Pro Namib at present. Historical trends of vegetation change indicate that modelled projections of decreases in precipitation (e.g. Christensen et al., 2007; Haensler et al. 2011b) in our study area are not yet apparent. Rather than an expansion of more arid-adapted species into more mesic environments, our analysis documents the incursion of

mesic species into more arid environments and an increase in woody plant cover in most localities. Closer examination of the historical photographs also shows that landscapes in the Central Namib generally had less cover with fewer woody plants in the first half of the 20th century relative to present.

It might be argued that by basing our findings on repeat photography we will always face a great deal of variability between sites because the landscape itself is not uniform and not all sites have responded to changes in climate in the same way. The role of increased atmospheric CO_2 levels in improving the water use efficiency of C_3 woody plants in particular could also partially account for the increases in woody cover change. However, the most parsimonius explanation for the increase in biomass is the increase of fog occurrence in the Fogbelt and a westward expansion of convective rainfall in the Savanna transition and the eastern Grass/shrublands. Our evidence suggests that synoptic scale weather patterns have changed in ways that contradict many of the regional climate model forecasts but that the projected effects of global warming on the Benguela upwelling system accord most closely with our evidence of change in this arid and hyper arid environment. The fact that the Namib and Pro-Namib environments are overwhelmingly influenced by the Benguela current provides an explanation as to why they are de-coupled from the effects of global warming across other parts of southern Africa.

These findings are important for a number of reasons including the value of evidence-based knowledge for recalibrating regional GCMs, forecasting risk to rare desert biota, predicting sustainable use of alluvial water resources and enhanced understanding of the BUS and other Eastern Boundary Upwelling Systems.

Declarations of interest

None.

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Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.jaridenv.2019.01.007.

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